A COMPACT PARALLEL PLATE WATER CAPACITOR

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ABSTRACT

A low inductance high energy density parallel plate water capacitor has been designed for driving currents through an inductive load. The design is an extension of the ZFX parallel plate water capacitor (350 kJ, 750 kV) in which the field enhancement at the edge of the plates is eliminated by using thick structures that are fully radiused at the ends. The new concept uses thin plates with the enhancement reduced by placing a plastic field attractor (PFA) at the edge of the plate. This approach has been successfully tested on a small scale (250 J, 890 kV) module, and a full scale system (340 kJ, 1 MV) has been designed and is under construction. This water capacitor is inexpensive, mechanically simple, easy to maintain, and very compact. In fact it would be almost nine times smaller than a single coaxial line with the same performance.

INTRODUCTION

Several pulsed power applications require currents on the order of 1-2 MA to be driven through an inductive load. Typically the total system energy is about 300 kJ and the current is driven with risetimes on the order of 500-1000 nsec. Examples of such requirements are the dense z-pinch[1] and the plasma erosion opening switch[2]. In most cases the generator consists of a water dielectric intermediate store that is pulsed charged by a Marx generator and then discharged through an output switch into the load. While the dramatic increase in energy density of commercial high voltage capacitors[3] has allowed the Marx to become increasingly smaller, the energy density of this intermediate store has not echoed this trend and now dominates the size of the driver. This is because the store is usually configured as a coaxial line, which is inherently a volumetrically inefficient device for storing energy: Only the water between the conductors can be used. Yet in order to have a reasonably low impedance, the inner and outer conductors must have close to the same radii, from which it follows that the large volume inside the inner conductor is wasted. A far more efficient approach would be to configure the intermediate store as a water capacitor that is constructed of alternately charged thin parallel plates.

The problem with such an arrangement is the field enhancement at the edge of the plates. This is shown dramatically in Figure 1, where the equipotential contours are computed[4] for a 2.5 cm thick plate that is separated from two outer plates by a distance of 12.5 cm: While the field between the plates is uniform at 80 kV/cm (which, as shown in the appendix, is comfortably below the 92 kV/cm allowed electrical stress), that at the edge of the plate is as high as 360 kV/cm and far exceeds the threshold for electrical breakdown in the water.

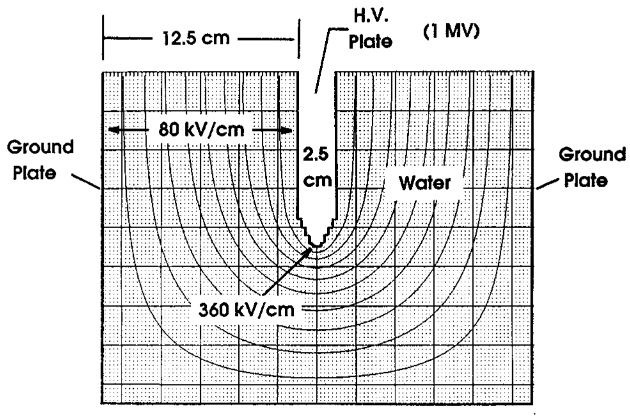

Figure 1: Equipotential plot of the edge of a thin plate surrounded by plates charged to the opposite polarity. (The stepped electrode edge is an artifact of the plotting program; the surface is actually smooth.)

One way to reduce this enhancement is to make the plates as thick structures with a full radius on the edges. This was the approach used in the NRL ZFX generator[5]. However this still is still fairly inefficient as the volume displaced by the thick sheets is wasted.

THE PFA CONCEPT

A more efficient approach is to make the plates from thin sheets and place a plastic block between the edge of the sheet and the opposite wall. As shown in Figure 2, the lower dielectric constant of this plastic field attractor (PFA) redistributes the equipotential surfaces and greatly reduces the stress in the water. The field in the water is mostly uniform at 80 kV/cm with a small region as high as 108 kV/cm. This is below the threshold for water breakdown (see the Appendix). The field along the interface is less than 80 kV/cm and that inside the plastic is less than 185 kV/cm. These are also below the threshold for breakdown.

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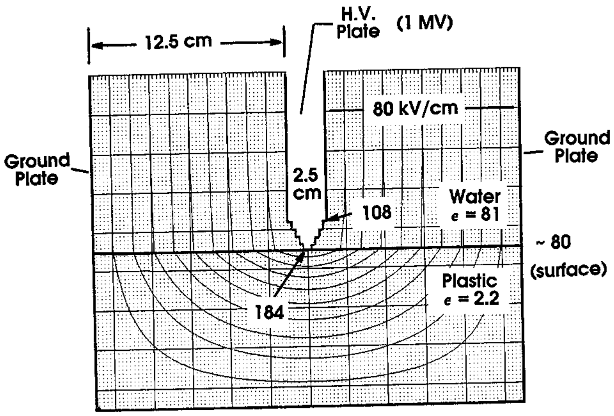

Figure 2. Same configuration as in Figure 1, except a plastic block has been placed at the edge of the plate.

MODULE TEST

The PFA concept was tested on the half voltage, full field module shown in Figure 3. The plates were constructed of aluminum, with the high voltage electrode 4.0 cm in radius and 1.27 cm thick, and the spacing between the plates 6.25 cm. The plastic is polyethylene and was chosen for its low cost. Note that the arrangements in Figure 3 tests the PFA concept in both polarities: The plastic must reduce the field enhancement at both the edge of the electrode (negative) and the feed (positive). The water was deionized (approximately 1 MΩ-cm) and deaerated by pumping on the module beforehand with a vacuum pump. This latter step was very important as any trapped air bubbles would virtually guarantee water breakdown. The electrodes, on the other hand, were left unpolished in order to duplicate the actual condition of the material that was to be used, and there was a deliberate .3 cm gap in the plastic (see Figure 3) in order to simulate small tolerance mismatches in actual construction.

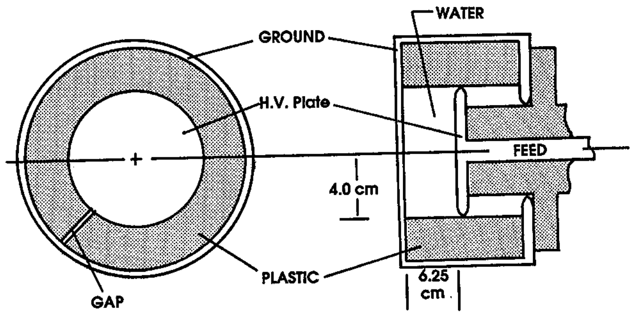

Figure 3. Module used to test the PFA concept

The eventual application of the full scale water capacitor (driving a dense z-pinch load) requires a τ_{eff} of 1.4 μsec, a charging voltage of 1000 kV, and a total plate area of 10^6 cm^2. τ_{eff} is defined as the time the voltage is above 63% of its maximum and could be closely matched by the test. However the area of the module is only 650 cm^2, and as the breakdown field scales as $A^{-.058}$ (see the appendix), this implies the module must holdoff at least 1000 kV/2 x $(650/10^6)^{.058}$ = 765 kV in order to be a proper test. (The factor of two arises because the module is half scale.)

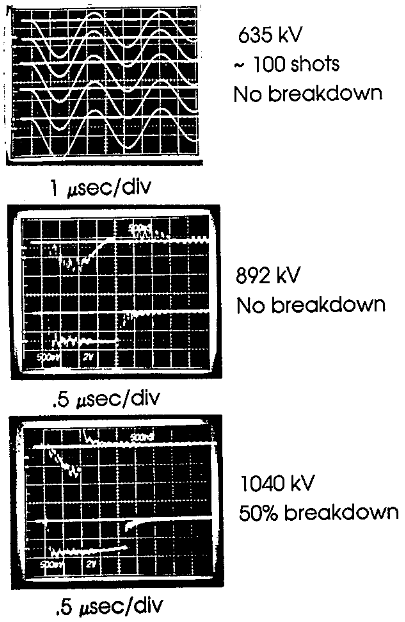

Figure 4. Results of module test.

Figure 4 shows the results of the module test. In the upper photo the module is charged to 635 kV with τ_{eff} = 1.2 μsec by a small trigger Marx and allowed to ring for several cycles. No breakdown was experienced in over 100 shots. In the middle photo the module is driven by a larger Marx, which also has τ_{eff} = 1.2 μsec, but has a divertor that truncates the pulse after 2 μsec[6]. No breakdown was observed at 892 kV on the module. This corresponds to over 1165 kV on the full scale water capacitor, or a 14% safety margin. In the lower photo the module charged to 1040 kV. In this case the module broke down in two out of four attempts. The breakdown channel started at the highest field point on the high voltage (negative) plate (the 108 kV point in Figure 2), transferred to the plastic interface approximately 2 cm from the plate edge, and remained on the interface until it intersected the ground electrode. When these tests were completed, the plastic was removed entirely and the module broke down at 700 kV; a gratifying indication that the plastic is doing its job. Thus it is fair to conclude that the full scale water capacitor would probably breakdown 50% of the time if charged to 1350 kV, which is 135% of its design value.

WATER CAPACITOR

A water capacitor based on this concept is under construction and is shown in Figure 5. It will store 340 kJ at 1 MV (capacitance of .68 μF) and be capable of driving 1.8 MA through a 210 nH load. The capacitor is housed in two boxes that are 2.9 m long by 2.4 m wide by 1.5 m high so the total volume is 20.8 m^3. The high voltage plates are made of 2.54 cm thick aluminum, and the ground plates, which are designed to have no field enhanced edges, are made of 1.27 cm thick aluminum plate. The aluminum has an irridite coating to prevent long term corrosion. The polyethylene in the straight sections is cut from standard 4" thick, 8' x 4' sheet and the corner pieces are cast. (The corners must have a radius of 30 cm to keep the fields reasonable.) The high voltage plates rest on the plastic with a 3 mm gap at the sides. The gap has shown to be acceptable by both computation and experiments and it greatly facilitates assembly.

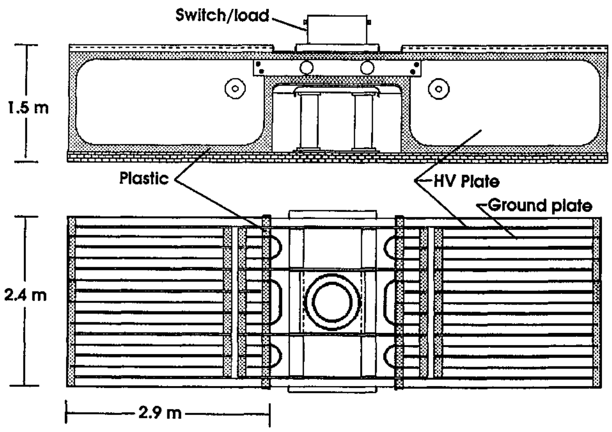

Figure 5. A 340 kJ, 1 MV water capacitor based on the PFA concept.

This device is quite compact. At a uniform field, E = 80 kV/cm the energy density is $w_{max} = \epsilon_0 \epsilon E^2/2 = 22.9$ kJ/m^3, where ϵ_0 is the permittivity of free space = 8.85 x 10^{12} and ϵ is the dielectric constant of water = 81. This water capacitor will store 340 kJ in 20.8 m^3, or w_{pfa} = 16.4 kJ/m^3. Put another way, 16.4/22.9 = 72% of the available volume is used to store electrical energy. In contrast, a coaxial based system with the same performance uses only 9.2% of the available volume, and would be 7.4 times larger.

This approach has other advantages: it is inexpensively constructed from standard mill-size material; bubbles in the water are easily removed because all surfaces are vertical; the thick plates make a very robust structure able to withstand a breakdown at full charge; the plates can be lifted straight out and replaced without moving the capacitor, Marx, or load; and, the symmetry of the plates allow the capacitor to be charged in either polarity or take a voltage reversal with far less chance of breakdown. In addition, this system should also have a low inductance because the discharging capacitor can look like several parallel plate transmission lines. Based on the experience with the dimensionally larger ZFX it is expected that the inductance of this capacitor should be on the order of 15 to 20 nH.

CONCLUSION & ACKNOWLEDGEMENTS

The idea of using plastic to redistribute the electric field in a water-dielectric medium is not new, however the application on such a large scale to build a high energy density system is. The author gratefully acknowledges stimulating conversations with A.E. Robson and the competent technical assistance of K.A. Gerber, J.P. Picciotta, and E.C. Laikin. This work was sponsored by the Office of Naval Research.

APPENDIX - MAXIMUM STRESS ON CAPACITOR

Because the capacitor is symmetric, the breakdown from the positive surface will dominate. The maximum allowable stress is given by[7]:

$$E_{br}[\text{kV/cm}] = 230/\tau_{eff}^{.33}A^{.058},$$

where τ_{eff} is time (in μsec) the voltage is above 63% of its maximum, and A is the conductor area in cm^2. In the case of the PFA based water capacitor, τ_{eff} = 1.4 μsec and the area in the uniform field regions is A ~ $10^6 cm^2$. Thus, E_{br} = 92 kV/cm, or 1.15 times the maximum design field of 80 kV/cm. For the higher stressed edges of the plates, A is 5000 cm^2 and E_{br} = 125 kV/cm, which is 1.16 times the maximum design field. Thus at maximum charge the capacitor should be at no more than 87% of breakdown. This is consistent with the module results.

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